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Teardown Analysis of a Ten Cell Bipolar Nickel-Hydrogen Battery

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ABSTRACT

Design studies have identified bipolar nickel-hydrogen batteries as an attractive storage option for high power, high voltage applications. A pre-prototype Ni-H$_2$ battery was designed, assembled and tested in the early phases of a concept verification program. The initial stack was built with available hardware and components from past programs. The stack performed well. After 2000 low-earth-orbit cycles the stack was dismantled in order to allow evaluation and analysis of the design and components. The results of the teardown analysis and recommended modifications are discussed.

INTRODUCTION

Future space power storage requirements are projected to far exceed the present levels of 0.5 to 1.0 kW. Current trends for multikilowatt use are toward high voltage (100 to 250 V) and high capacity systems. The bipolar nickel-hydrogen (Ni-H$_2$) battery under development at the NASA Lewis Research Center has many features that make it attractive for these high power applications. Preliminary designs of the bipolar Ni-H$_2$ system indicate improved energy densities over the nickel-cadmium (Ni-Cd) systems currently used for energy storage in space, and the individual pressure vessel (IPV) Ni-H$_2$ system currently challenging the Ni-Cd systems. In addition, from an overall systems level, the bipolar battery offers advantages in the area of integration, having 2 to 3 orders of magnitude fewer units to manage and control than comparable individual cell systems (1).

A pre-prototype Ni-H$_2$ battery was designed, assembled, and tested in the early phases of a concept verification program. The design incorporated hardware obtained from Life Systems, Inc., some components available from past programs, and other components specifically constructed for this application. A 10 cell, 6.5 amp-hr stack was constructed and tested. Performance was characterized at various charge and discharge rates. Following the characterization tests, the battery was cycled on a low-earth-orbit (LEO) regime at 80% depth of discharge (DOD). After completing 100 cycles, the peak power capabilities were evaluated. Cell one was then removed for evaluation and analysis. The remaining nine cells were returned to test at 80% DOD on the LEO regime. After 2000 LEO cycles the battery was removed from testing and dismantled for a teardown analysis. At the time of teardown the battery was still operating satisfactorily. It was dismantled in order to allow evaluation and analysis of the design and components.

In this paper the construction and cycle history are briefly reviewed, the teardown of the stack is described and the results of the analyses are discussed. Based on these results, design modifications were recommended.

STACK HARDWARE AND COMPONENT DESIGN

In order to expedite the bipolar concept verification testing, hardware (frames, bipolar plates, end plates, tie bolts, and insulation plates) for fabricating the bipolar battery was obtained on loan from Life Systems, Inc. of Beachwood, Ohio. The hardware was originally used in a carbon dioxide removal unit used for life support on the Apollo missions. The basic design of the bipolar Ni-H$_2$ battery was easily adapted to the frame configuration. The frame and stack configurations are shown in Fig. 1.

As part of the initial assessment of the concept, electrolyte management and oxygen management were identified as areas that needed to be addressed in the stack design and configuration if the system was to have long life at deep depths of discharge. In order to keep the oxygen generated at the nickel electrode on charge and overcharge from recombining on and possibly damaging the hydrogen electrode, a high bubble pressure asbestos separator was used. This causes the oxygen generated to be forced off of the backside of the nickel electrode and into the electrolyte reservoir plate (ERP). The ERP is equipped with recombination sites which consist of catalyzed strips (hydrogen electrode) inside a porous tube which allows the transport of gases in and water vapor out and electrically insulates the catalyst from the

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nickel electrode. The hydrogen and oxygen recombine to form water at the catalytic surface, the water (as vapor) diffuses from the tube back into the ERP and eventually into the nickel electrode due to vapor pressure differences. This method of oxygen management also aids electrolyte management by keeping the concentration of electrolyte within a cell more balanced. It also keeps the recombination product water near the nickel electrode from which it was formed and away from the hydrogen electrode to prevent flooding. The objective of electrolyte management is to keep the proper distribution of electrolyte in the components as changes resulting from cycling occur in the battery. This can be accomplished through proper pore size engineering of the porous components of the cell (2).

Electrolyte management is further aided by the use of the ERP and wick rings. The ERP serves as a highly porous reservoir that can freely accommodate the recombination product water and also provide electrolyte to the separator and the nickel electrode as the average pore size of the nickel electrodes shifts to smaller sizes with cycling. The ERP is in contact with the separator by a set of wick rings which encompass the perimeter of the nickel electrode. The rings also function to form a seal with the separator to prevent the escape of oxygen into the pressure vessel.

Electrolyte Reservoir Plate - The ERP was a nickel foam metal with a nominal pore size of 0.051 cm. The ERP was cut to measure 11.74 cm by 23.25 cm by 0.120 cm thick. As received the ERP was 0.254 cm thick, the thickness was adjusted to 0.120 cm to accommodate the frame thickness. The ERP extended 1.58 cm beyond the edges of the nickel electrode in each direction. It had four slots along its length 8.0 cm by 20.7 cm for the recombination strips described above.

Nickel Electrode - The nickel electrodes used for the bipolar battery were left over from a previous program. The sinter for the nickel electrode was made by the pressed powder method with a nickel screen substrate. The plaque was chemically impregnated to a loading of 2.1 g/cc void volume. The electrodes measured 10.2 cm by 21.7 cm by 0.10 cm. The length and width were each 0.47 cm shorter than the opening available inside the wick rings to allow for expansion. The theoretical capacity of the electrode was 9.1 amp-hr based on the loading and an 85% utilization of the active material. The actual capacity of the electrode was 6.5 amp-hr determined at the C/4 rate (where C represents the cell capacity).

Separator and Wick Rings - The separator used in the bipolar stack was beater treated asbestos (BTA). This is a reconstituted fuel cell grade asbestos sheet that has been blended with 5% butyl laytex binder and cast in a one ply 0.017 cm sheet. Three layers of the 0.017 cm material were used and compressed to 0.025 cm. The separator extends beyond the edges of the electrodes by 1.6 cm and sits on a shelf in the frame. The dimensions of the separator are equal to the outer dimensions of the wick ring. The wick ring consists of three layers of the 0.017 cm beater treated asbestos and two layers of 0.025 cm fuel cell grade asbestos. This helps form the seal that prevents the oxygen produced at the nickel electrode from reaching the hydrogen electrode and promotes wicking.

Hydrogen Electrode - The hydrogen electrode consists of a platinum Teflon mix deposited on a porous metal screen. The screen is gold plated nickel. Manufacturing details and other electrode properties are proprietary to the manufacturer. The dimensions of the hydrogen electrodes used in the stack are 10.2 cm by 21.7 cm by 0.025 cm.

Gas Flow Screen - The gas flow screen at the back of the hydrogen electrode is an expanded nickel mesh that was 0.15 cm thick as received and compressed to 0.11 cm to accommodate the frame dimensions in the hydrogen cavity. The screen has approximately 95% open area.

Assembly - The components were assembled in the stack as shown in Fig. 1. After assembly the entire stack was vacuum filled with 32 wt % potassium hydroxide (KOH). The KOH was allowed to stand in the stack overnight then the excess electrolyte was drained out. Following the drain, the ports and manifolds were cleaned of any excess KOH. The stack was placed vertically in the pressure vessel. The test chamber was evacuated and filled with hydrogen to 3.4 atmospheres (50 psi).

Test Summary - The initial tests run on the battery indicate that its capacity was 6.5 amp-hr determined at the C/4 rate on discharge. Battery performance was characterized at various charge and discharge rates. The stack was then cycled at 80% DOD on a LEO regime which consisted of a 1 hr charge followed by a 0.5 hr discharge. At 80% DOD and with a charge to discharge ratio of 1.1 the charge and discharge rates were 0.88 C and 1.6 C respectively. (The capacity was determined to be 6 amp-hr at the currents used for the LEO regime.) After the first 100 LEO cycles the peak power capabilities of the stack were determined. Following the

peak power test, cell no. 1 was removed from the stack. The cell was removed for evaluation purposes, no anomolies were present at the time of removal. The components were examined in order to identify possible problem areas early on in life. The stack was reassembled with the remaining nine cells, refilled with electrolyte, drained and placed in the pressure vessel horizontally with the ERP/nickel side down. The vessel was again evacuated and filled with hydrogen to 3.4 atm and the stack was returned to LEO cycling on the regime described above. The battery accumulated a total of 2000 cycles before it was removed from test for analysis.

During cycling, the weaker cells in the stack would periodically exhibit low end of discharge voltages. This degradation was attributed to the presence of shunt currents. It was necessary to increase the recharge ratio from 1.1 to 1.2 to maintain end of discharge performance. However, the voltages did not remain stable. Deep discharge reconditioning was found to be effective at rejuvenating the battery. When the end of discharge voltages fell much below 1.0 volt deep discharge reconditioning (drain with a 10 ohm resistor and short circuit overnight), followed by a C rate charge for two hours did successfully equilibrate cell performance within the battery. After deep discharge reconditioning, the end of discharge voltages returned to their original values of 1.20 volts.

The battery was dismantled after 2000 cycles in an effort to identify areas which might require modification, so that any recommended changes could be incorporated in the design of a 1 kWh bipolar nickel-hydrogen stack. More detailed descriptions of the battery construction and test results are available in Ref. 3.

EXPERIMENTAL PROCEDURES

Each time the test chamber was opened visual observations were made and the conditions of the stack and vessel interior were noted. Before dismantling, the torque on all of the bolts was checked. As cells were removed from the stack all components were examined and photographs were taken of any areas of interest. Samples of any unusual substances were saved for analysis.

As the active materials were removed from the stack they were labeled and stored in plastic bags. In order to prevent carbonation of the electrolyte in the components the bags were stored in a dry box in an argon atmosphere until the samples could be analyzed. The dimensions and weight of each component were measured upon removal from the

stack in order to monitor possible growth and/or expansion. The electrolyte was extracted from samples of each component and analyzed for KOH concentration and carbonate concentration. An effort was made to determine gradients within and across a cell as well as between cells. The procedures for extraction and analysis of the electrolyte are similar to those described in Ref. 4.

Nickel Electrode - In addition to the above measurements, the remaining capacity and the flooded capacity of the nickel electrodes were measured. The remaining capacity of the nickel electrode in the area of the recombination strips was measured and compared to the remaining capacity of an adjacent area. The flooded capacity was measured and compared to the flooded capacity of unused electrodes of the same type in order to determine if there was any permanent loss of capacity. All of the capacity tests were run against an oversized nickel counter electrode; an amalgamated zinc electrode was used as the reference electrode. The capacity was measured based on a C/2 rate charge and a C/4 rate discharge. Samples of the nickel electrodes removed at 100 cycles and at the end of testing were sent for multiple point surface area analysis and porosimetry by mercury intrusion in order to monitor changes that took place with cycling.

Hydrogen Electrode - The hydrogen electrodes should not suffer any degradation due to cycling and as a result they were intended for reuse. One hydrogen electrode was sacrificed for testing. Samples of the electrode were inspected with a scanning electron microscope (SEM). Samples of a new electrode were also examined and the results were compared. Samples of the hydrogen electrode were also set aside for porosimetry, polarization tests, and electrolyte extractions.

Separator - The separator was fully characterized before it was used in the battery. The screening tests were repeated on samples from each cell removed from the battery. Area resistivity, volume resistivity, hydroxyl diffusion, electrolyte retention, porosity and pore size were measured and compared to the initial results. In addition, bubble pressure was measured on the initial samples however, it could not be measured on samples from the battery because the size sample required could not be obtained. Details of the above procedures are explained in Ref. 5.

Recombination Strips - Samples of the recombination strips and the porous tube that encompassed them were examined with the SEM, the SEM pictures were compared to those from unused samples.

Electrolyte Reservoir Plate - Samples of the electrolyte reservoir plate were retained for electrolyte analysis.

RESULTS AND DISCUSSION

When the test chamber was opened at the end of the first 100 cycles, visual observations showed that a considerable amount of electrolyte had drained or been forced from the stack and formed a pool at the bottom of the pressure vessel. This indicates that there are possible problems with the electrolyte reservoir plate and/or the fill and drain procedure. The ERP used in this stack has a nominal pore size of 0.051 cm. Experiments have shown that an ERP with this pore size most effectively holds electrolyte when horizontal. Therefore it is possible that once the stack was mounted vertically in the vessel, electrolyte that was effectively held horizontally worked its way free and drained from the stack. It is also possible that the stack was not drained sufficiently before being placed in the vessel, electrolyte may have been forced from the stack during evacuation of the pressure vessel preceding the hydrogen fill or it may have been forced out during the initial charge. The fill procedure that was used is probably also partially responsible for the shunt currents which developed during cycling. The stack was vacuum filled through the manifolds that allow hydrogen access to the cells. It was not possible to completely remove the electrolyte films left from filling and these films probably contributed to the electrolyte bridges that were formed.

When the stack was removed from the vessel, corrosion was evident in the manifold on the positive end of the bipolar plates. The deposits were greenish in color. Analysis identified them as nickel compounds. The substance was probably nickel nitrate or nickel carbonate. Again, the electrolyte film left from the fill procedure probably contributed to the corrosive reactions.

The components of the cell (one) that was removed from the stack after the first 100 cycles showed few signs of degradation. The hydrogen electrode looked much as it did when it went into the stack. Visually, the nickel electrode was beginning to develop a pattern that differentiated the area adjacent to the recombination strips from the rest of the electrode. The nickel electrode had begun to swell, the thickness had increased from 0.101 to 0.112 cm in the areas adjacent to the recombination strips and to 0.122 cm in the other areas. The nickel electrode also expanded along its length and width approximately 0.159 cm in each di-

rection. There were no obvious differences in the ERP, the separator, or the gas flow screen.

The stack was reassembled with the remaining nine cells, vacuum filled and drained before being placed in the test chamber. A longer time was allowed to insure that the stack was sufficiently drained. The test chamber was evacuated and filled with hydrogen to 3.4 atm and LEO testing was resumed. The vessel was opened several times over the course of the next 1900 cycles to clean the manifolds of excess KOH or to reposition the stack in the chamber. Free electrolyte was found in the manifolds but no more electrolyte was found in the bottom of the pressure vessel. When the stack was removed from the vessel at the end of 2000 LEO cycles electrolyte was found along the sides of the stack, bubbling out between the bipolar plates. This possibly resulted from leaks in the gasket seals that developed when the compression on the stack was relieved to remove cell one. More corrosion was evident inside the manifold areas of the stack.

As the stack was disassembled, the components from each cell were visually examined and their weights and dimensions were measured. In general, the hydrogen electrodes looked much as they did when they were new. There was however, evidence that the gas flow screen was tightly compressed against the electrode as the grid pattern was clearly visible, especially in the areas corresponding to the position of the recombination strips. The condition of the separators upon removal was also excellent. There was no apparent degradation of the separator integrity. It too showed signs of extreme compression. The gas flow screen pattern was visible on the hydrogen side of the separator and the grid pattern from the nickel electrode was impressed on the nickel side. The nickel side of the separator was also somewhat blackened with active material from the electrode. The nickel electrode appearance changed drastically. A photograph of the nickel electrode removed from the stack is shown in Fig. 2. The areas corresponding to the position of the recombination strips were distinct. Here the surface of the nickel seems to have conformed to the strip. The recombination strips did not completely fill the slots, they were slightly thinner and approximately 1.27 cm shorter than the slots. The nickel electrode expanded into this open space and in some places extended all of the way to the bipolar plate. The active material in these areas was extremely dense compared to the rest of the electrode. The nickel electrode expanded from its original thickness of 0.101 to 0.145 cm in the plate area and to 0.165 cm in

the areas adjacent to the recombination strips. In the open areas of the slots the thickness of the nickel electrodes varied from 0.178 to 0.254 cm at the ends and up to 0.241 cm along the sides. In these areas of extreme expansion a slight indentation was left in the separator side of the electrode. The limits on expansion, up to 0.254 cm, correspond to the combined thickness of the expanded nickel electrode and the ERP. Thus, it may be that the electrode grew into these areas because the space was available and offered little resistance to expansion. Since recombination was taking place on the recombination strips the local concentrations of the electolyte in these areas was lower than elsewhere in the cell. The active material, $NiOH_2$, dissolves as the nickelite ion ($HNiO_2^-$) in highly concentrated solutions of KOH. It is also possible that this dissolved species could migrate to the areas around the recombination strips, where the concentrations of the electrolyte would be the lowest, and precipitate, resulting in increased thickness in these areas (6).

The nickel electrode is the only component whose dimensions change appreciably. The area (length x width) increased by 5% and as stated above there was a 50% increase in electrode thickness. The expansion of the nickel electrode is responsible for the increased compression on the components in the stack. The total thickness of all components new was nominally 0.406 cm compressed to 0.378 cm. It was assumed that the 0.053 cm separator would take up the required compression of 0.028 cm. Following 2000 cycles the total thickness of all of the components was 0.437 cm (the average value for nine cells), the average thickness of the separator was 0.043 cm. This total thickness was compressed to the frame thickness of 0.379 cm, a total compression of 0.058 cm. The separator was probably compressed to less than 0.043 cm in the stack but cannot alone account for the total compression. It is possible that the ERP or the gas flow screen took up some of the compression and was resilient enough to spring back to a value approaching its original thickness. The average thickness of the ERP's decreased from the nominal original value of 0.119 to 0.112 cm, the gas flow screen was compressed 0.013 cm from 0.107 to 0.105 cm. Alternately, or in addition, the nickel electrode may not have fully expanded until the compression on the stack was released. In any event, there was evidence of excessive pressure on the cell components that can be attributed to the expansion of the nickel electrode.

The ERP had a considerable amount of nickel active material distributed in it. The presence of the nickel active material in the ERP might also be attributed to the relative solubilities of the NiOH2 in various concentrations of KOH. The electrolyte in the ERP would again be less concentrated due to recombination and active material dissolved in the electrolyte may have migrated into the ERP and precipitated there. In some cases the active material went completely through the ERP leaving a pattern on the bipolar plate (fig. 3). The active material was deposited along the lines of the gas flow screen at the edges. This can be attributed to two factors: (1) The active material was deposited along the lines of high current density which corresponded to the gas flow screen contact points, and/or (2) the excessive pressure on the stack may have resulted in the nickel being deposited in the contact areas. As mentioned above, the ERP may have been slightly compressed by the expansion of the nickel electrode.

Following removal from the stack the components were examined more closely. The following is a discussion of the observations and results:

Hydrogen Electrode - SEM photographs of new and used hydrogen electrodes were taken. There were no noticeable differences between the new electrodes and those which had 100 or 2000 cycles, other than that the photographs of the electrodes that had been in the cells showed the presence of asbestos fibers on the electrode surface. Samples of the hydrogen electrodes were saved for further analysis however, the electrolyte dried out very quickly leaving KOH crystals and areas where the catalyst separated from the substrate. As a result no further tests were run on the hydrogen electrodes, there were no samples available for polarizations, extractions and/or pore size analysis.

Separator - The separator material was thoroughly characterized before and after cycling. From the data presented in table I, it can be seen that there were no significant changes in the separator properties after 100 or 2000 LEO cycles in the bipolar NiH_2 battery.

Nickel Electrode - The results of the remaining capacity and flooded capacity tests run on the nickel electrodes are shown in tables II and III. Because of the obvious differences in the morphology of the nickel electrodes in the area corresponding to the recombination strips and the other areas of the electrodes the two areas were evaluated and compared for both remaining and flooded capacity. The results of the remaining capacity tests show that there was slightly more capacity remaining in the nonstrip areas however this difference is extremely small

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and may not be significant. The flooded capacity tests results show that there was no permanent degradation of capacity as the strip areas had a greater capacity per unit area than the nonstrip areas.

An additional section of the nickel electrode, which included both types of areas was tested for flooded capacity and compared to control samples of previously uncycled nickel electrodes from the same lot as those used in the stack. The results, shown in table III indicate that there was no degradation in electrode capacity after 2000 LEO cycles. The flooded capacity of the nickel electrode calculates to 7.68 amp-hr, this is only 72% of the theoretically available capacity. Highly loaded electrodes typically do not offer maximum utilization of the active material.

The results of the pore size analysis by mercury intrusion are shown in Fig. 4. A sample of the electrode at 100 cycles is compared to an electrode at 2000 cycles. The results were as expected. The number of small pores increased in the cycled electrode. The surface area analysis results also support this conclusion. The surface area of the nickel electrode increased from 38 m^2/g at 100 cycles to 51 m^2/g after 2000 cycles.

Electrolyte Concentration and Distribution - The analysis of electrolyte from the various components initially showed a gradient in the concentration from cell 2 to cell 10 with the concentration of KOH increasing from approximately 30% KOH in cell 2 to 37% KOH in cell 10. It was determined that this was not an actual gradient but rather resulted from the way in which the analysis was conducted. The samples were stored in a dry box in an argon atmosphere to prevent carbonation of the electrolyte in the components because the ability for performing the extractions was limited to one per day. In addition, the samples were run in numerical order from cell 2 to cell 10. The argon atmosphere turned out to be too dry and the water in the electrolyte was gradually drawn out of the components, this showed up as an increased concentration of KOH. From the results of the analyses on the separator and the nickel electrode conducted shortly after the teardown it can be concluded that the concentration of KOH did not vary significantly from its original value of 32%. The concentration of carbonate varied from 3 to 5% in the separators and from 8 to 10% in the nickel electrodes. There was no indication that the carbonate present resulted from the reaction of CO_2 with the electrolyte. It is more likely that the car-

bonate was present in the nickel electrodes as such.

The weight of each component was measured upon removal from the stack. Unfortunately there were no dry weights available to allow a complete analysis of electrolyte distribution and how it varied with cycling. However, the dry weights of the nickel electrodes and the separators were sufficiently uniform to allow a partial analysis. The weights of the separators, wick rings and nickel electrodes upon removal from the stack are shown in table IV. By comparing the weights of the components from cell one to those of the other nine cells it can be seen that during cycling electrolyte was drawn from the separator and into the nickel electrodes. The weight gain of the nickel electrodes is greater than the loss from the separator indicating that some of the electrolyte was probably provided by the ERP. Without the ERP the separator would have dried out to a much greater extent, as the small pores that developed in the nickel electrode with cycling would have drawn electrolyte from it and possibly resulted in reduced cell performance.

CONCLUSIONS AND RECOMMENDED MODIFICATIONS

The teardown analysis performed on the ten cell bipolar nickel-hydrogen stack at the NASA Lewis Research Center was helpful in pointing out some of the shortcomings of the design of the preprototype stack and its components. Based on the observations and results of the tear-down analysis several critical areas requiring design and/or procedural modifications were identified.

The following modifications have been recommended and implemented in a rebuild of this stack:

Nickel Electrode - The nickel electrode in this stack was chemically impregnated and highly loaded (2.1 g/cc void). In order to reduce expansion and growth it has been replaced with an electrochemically impregnated electrode with a loading of 1.6 g/cc void volume.

Separator - The separator thickness was decreased from 0.053 cm to 0.036 cm to allow more space for expansion of the nickel electrode. By reducing the effective compression on the separator, performance may suffer some initally, but as the cell cycles and the nickel electrode expands, performance should improve. In this way end of life performance can be improved.

Electrolyte Management - In order to control the location of electrolyte in the

stack components, the fill procedure was modified. The nickel electrode was vacuum filled with electrolyte and a premeasured amount of electrolyte was added to the separator and ERP of each cell as the stack was assembled. This eliminated the need to vacuum fill the entire stack and should help control the formation of electrolyte bridges that lead to shunt currents. In addition, the gas access ports in the frames and the nonactive areas of the bipolar plates have been Teflon coated in an effort to minimize electrolyte creep.

In addition to the above modifications a 1 kWh stack of our own design will incorporate the following:

(1) A new frame design which has no manifolds.
(2) Modifications to the ERP design that eliminate the fully open slots in which the recombination strips rest. The full slots have been replaced by depressions in the bipolar plate side of the ERP. This results in a continuous surface contacting the nickel electrode and should tend to limit the nickel electrode shape change.
(3) Active cooling.
(4) Instrumentation to fully monitor cell temperatures, oxygen content in the vessel atmosphere, and the humidity inside the vessel (7).

Areas still under investigation include:

(1) An effort to improve the ERP by reducing its average pore size from 0.051 cm to 0.010 cm so that it would more effectively hold electrolyte yet freely provide it to the other cell components as necessary.
(2) A study of the design and operation of the recombination strips.

(3) A study of compression, in an effort to better establish the optimum operating conditions of a bipolar stack.

The results of these and other tests will be used to establish design parameters and handling procedures for bipolar nickel-hydrogen battery systems.

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TABLE I. - SEPARATOR PROPERTIES

Cell number	Resistivity		Hydroxyl diffusion, moles/ cm^2-sec	Electrolyte retention, %	Porosity, %	Pore size, A
	Area, Ω-cm^2	Volume, Ω-cm				
1	0.257	2.90	---	150	75.5	1759
2	.086	2.87	4.51×10^{-5}	165	87.3	1502
3	.171	2.77	4.60×10^{-5}	138	62.6	1808
4	.166	2.77	4.39×10^{-5}	160	71.5	1758
5	.164	2.61	4.80×10^{-5}	161	74.5	1522
6	.155	2.87	4.70×10^{-5}	140	67.4	1893
7	.139	1.81	4.50×10^{-5}	162	89.5	1338
8	.130	1.67	4.69×10^{-5}	173	88.9	1308
9	.121	1.59	4.96×10^{-5}	---	----	----
10	.117	1.53	5.42×10^{-5}	172	----	1831
Control	0.064	2.40	5.31×10^{-5}	134	69.8	1941

TABLE II. - FLOODED AND REMAINING CAPACITY
OF NICKEL ELECTRODES; RECOMBINATION
STRIP AREA VS NON-STRIP AREA

Cell number	Remaining capacity, amp-hr/cm^2		Flooded capacity, amp-hr/cm^2	
	Strip	Nonstrip	Strip	Nonstrip
2	0.0058	0.0097	0.0326	0.0278
3	.0012	.0041	.0307	.0289
7	.0004	.0007	.0269	.0248
8	.0016	.0042	.0310	.0260

TABLE III. - NICKEL ELECTRODE FLOODED
CAPACITY MEASUREMENTS

Cell number	Flooded capacity, amp-hr/cm^2[a]
2	0.0365
3	.0364
4	.0333
5	.0314
6	[b].0285
7	.0305
8	.0326
9	.0345
10	.0332
Control	[c]0.0342

[a]Average of multiple determinations
  of two samples.
[b]One sample.
[c]Six samples.

TABLE IV. - WEIGHT OF COMPONENTS UPON
REMOVAL FROM THE STACK (grams)

Cell number	Separator	Rings	Separator + rings	Nickel electrode
1	-----	-----	34.34	79.70
2	22.53	8.56	31.09	89.20
3	20.13	9.09	29.22	89.17
4	20.84	9.46	30.30	88.09
5	22.46	10.59	33.05	91.25
6	21.68	9.98	31.66	91.58
7	22.47	8.43	30.90	91.88
8	21.97	8.18	30.15	87.16
9	22.20	10.13	32.33	85.63
10	20.69	9.33	30.02	90.23

.028

.119 ± .003 ELECTROLYTE
RESERVOIR
PLATE

BEFORE
COMPRESSION

.025

.025   NICKEL ELECTRODE

.025   .102 ± .008

.018

.018

.379 ± .0076

AFTER
COMPRESSION

.018

.018   SEPARATOR

.018

.025 ± .003 HYDROGEN ELECTRODE

FRAME   GAS FLOW SCREEN
.107 ± .0025
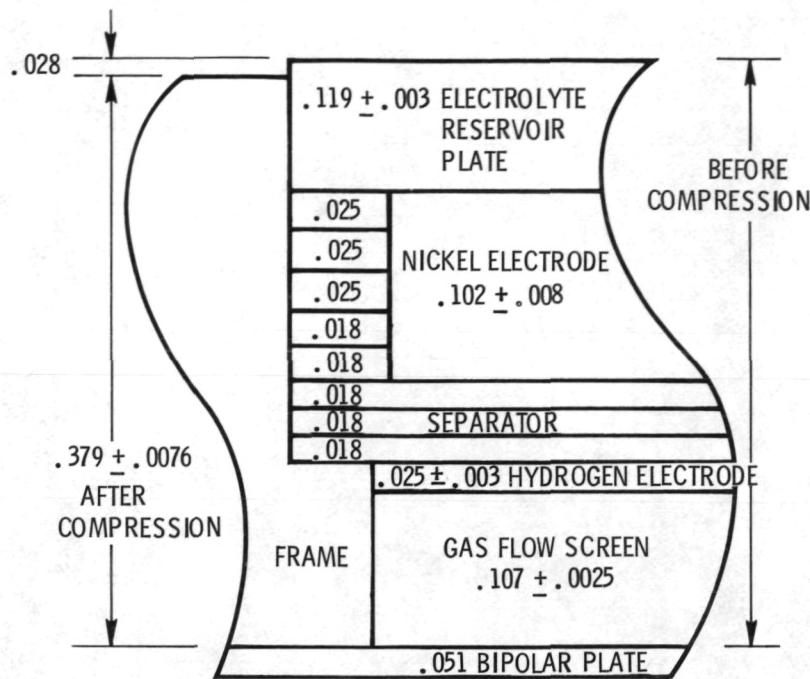
.051 BIPOLAR PLATE

Figure 1. – Cell cross section with dimensions of components, cm.

C-83-2367
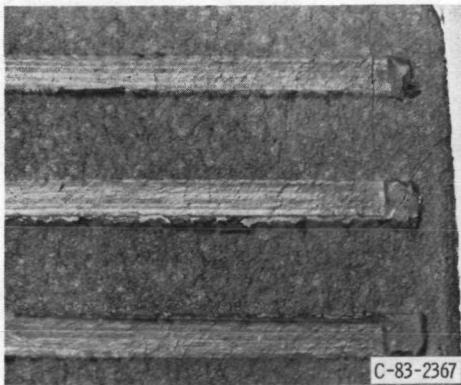
Figure 2. – Nickel electrode removed from bipolar stack
after 2000 cycles.

C-83-2366
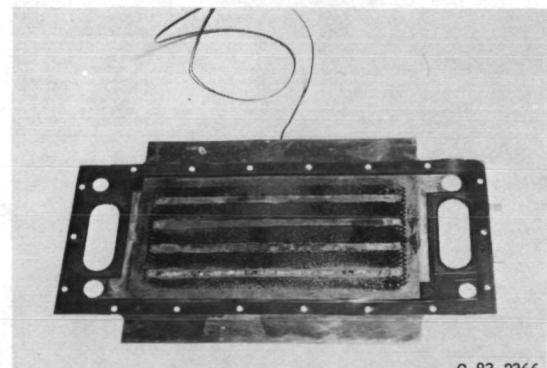
Figure 3. – ERP side of bipolar plate removed from stack
after 2000 cycles.
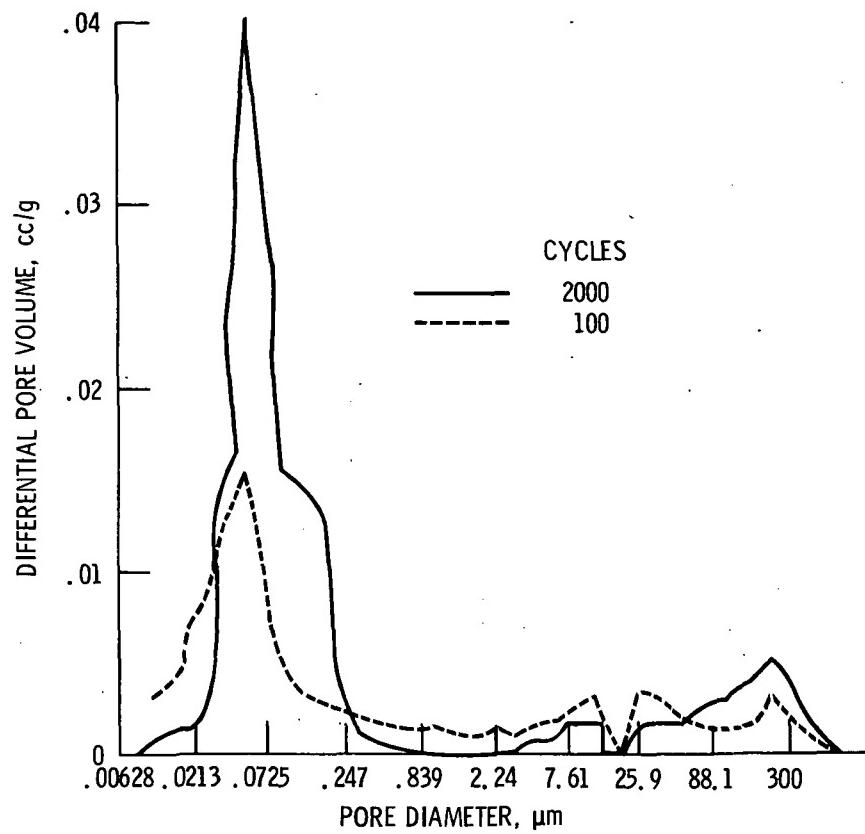
Figure 4. - Pore size distribution of nickel electrodes removed from bipolar stack.

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16. Abstract

Design studies have identified bipolar nickel-hydrogen batteries as an attractive storage option for high power, high voltage applications. A pre-prototype Ni-H_2 battery was designed, assembled and tested in the early phases of a concept verification program. The initial stack was built with available hardware and components from past programs. The stack performed well. After 2000 low-earth-orbit cycles the stack was dismantled in order to allow evaluation and analysis of the design and components. The results of the teardown analysis and recommended modifications are discussed.

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